

# Light Detectors

## EXERCISE 4-1

### EXERCISE OBJECTIVE

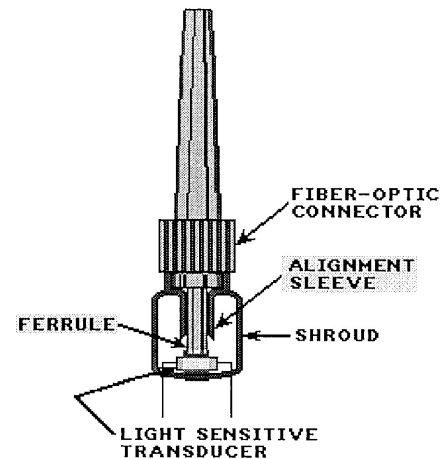
When you have completed this exercise, you will be able to describe the devices used in fiber optics to convert an optical signal into an electrical signal.

### DISCUSSION

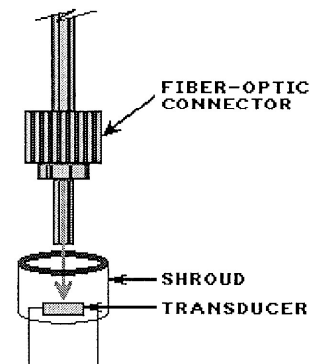
A fiber-optic light detector has a light sensitive **transducer** surrounded by a shroud.

The shroud insures that the optical fiber is the transducer's only source of radiant power.

To prevent losses, the shroud includes a sleeve that aligns the ferrule with the light-sensitive transducer.



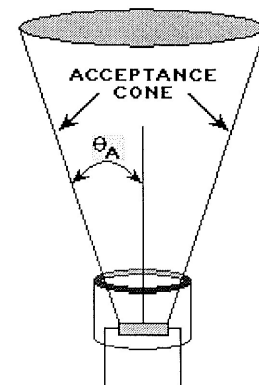
1. What type of transducers are used as fiber-optic light detectors?
  - a. light emitting diodes
  - b. phototransistors
  - c. photodiodes
  - d. Both b and c.



The light detector is not sensitive to light that is outside its acceptance cone.

A light detector has an acceptance angle ( $\theta_A$ ) and, therefore, a numerical aperture (NA).

$$NA = \sin(\theta_A)$$



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$$NA = \sin(\theta_A)$$

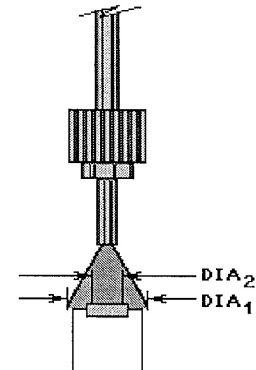
If the source (fiber) numerical aperture ( $NA_1$ ) is greater than the detector's numerical aperture ( $NA_2$ ) some of the radiant power is lost ( $LOSS_{NA}$ ).

$$LOSS_{NA} \text{ (in dB)} = 20 \times \log(NA_1/NA_2)$$

The detector cannot sense radiant power outside its **effective light-sensitive area**.

If the light diameter ( $DIA_1$ ) is greater than the **effective light-sensitive diameter** ( $DIA_2$ ), a loss of radiant power ( $LOSS_{UI}$ ) will occur.

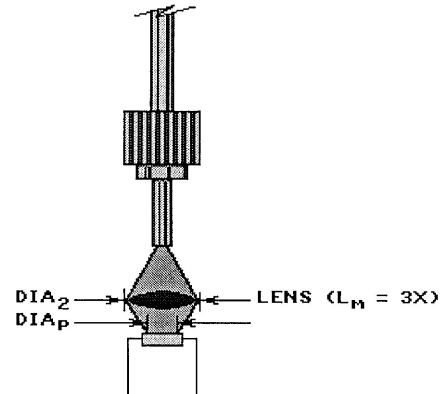
$$LOSS_{UI} \text{ (in dB)} = 20 \times \log(DIA_1/DIA_2)$$



If the detector has a lens, the transducer's effective light-sensitive area is increased.

Effective light-sensitive diameter ( $DIA_2$ ) is equal to the diameter of the transducer's physical sensitive area ( $DIA_P$ ) times the lens magnification ( $L_m$ ).

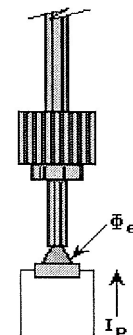
$$DIA_2 = DIA_P \times L_m$$



**Responsivity** ( $R_p$ ) is the ratio of the detector radiant input power ( $\Phi_e$ ) and the corresponding electrical output ( $I_p$ ).

$$R_p = I_p / \Phi_e$$

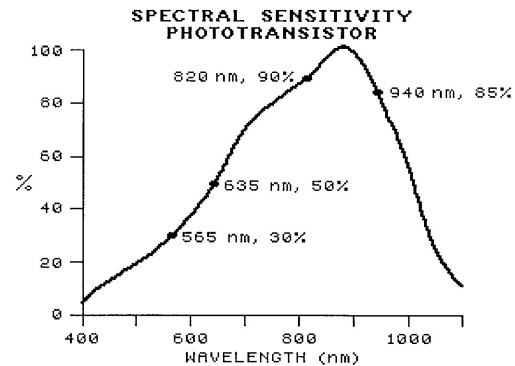
Responsivity is specified for a specific wavelength because detector sensitivity changes with wavelength.



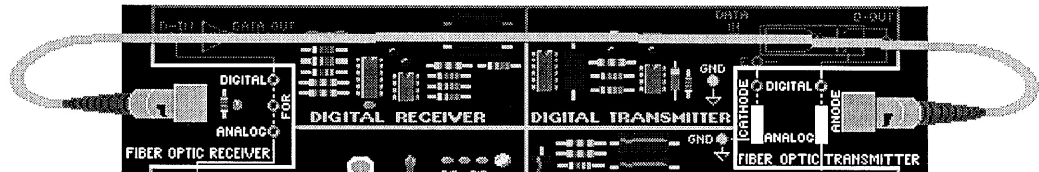
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2. What is the responsivity ( $R_p$ ) of this phototransistor at 635 nm if the responsivity is 2 mA/ $\mu$ W at 880 nm (100%)?

- 4 mA/ $\mu$ W
- 2 mA/ $\mu$ W
- 1 mA/ $\mu$ W
- 0.5 mA/ $\mu$ W

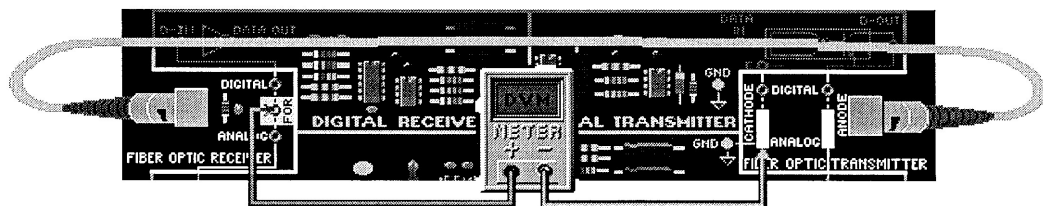
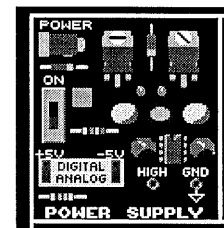


## PROCEDURE



1. Insure that all the two-post connectors and patch cords are removed from the circuit board.
2. Configure the FOT for analog transmission using two-post connectors.
3. Connect a 1m 65.2/125 glass fiber-optic cable between the fiber-optic transmitter (FOT) and the fiber-optic receiver (FOR).
4. Turn off the base unit power before moving the POWER SUPPLY shunts into the ANALOG positions.

Turn the base unit power on.



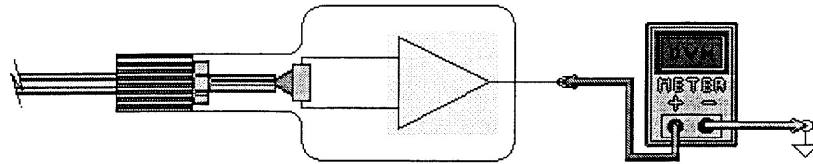
With the FOT in the analog configuration, the bias current typically provides 11.4  $\mu$ W of power ( $\phi_e$ ) at the end of the 1m glass cable.

5. Connect a DVM between the FOR output and ground.

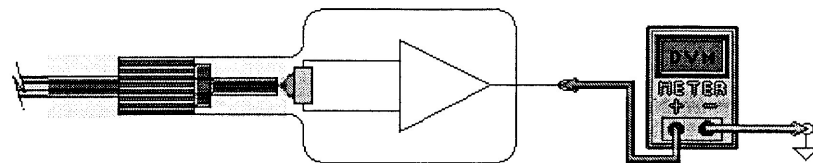
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6. Measure the DC voltage ( $V_{FOR}$ ) at the FOR output.

$V_{FOR}$  = \_\_\_\_\_ mV



The FOR uses an internal **transimpedance amplifier** to convert the photodiode current into the FOR output voltage.



7. Disconnect the fiber-optic cable from the FOR and measure the FOR output voltage ( $V_{FOR}$ ).

$V_{FOR}$  = \_\_\_\_\_ mV

| Light Power $\phi_e$ | $V_{FOR}$ |
|----------------------|-----------|
| Connected            | 650 mV    |
| Disconnected         | 730 mV    |

**NOTE:** The nominal values are given for your guidance here and on the following pages. However, use your values for calculations.

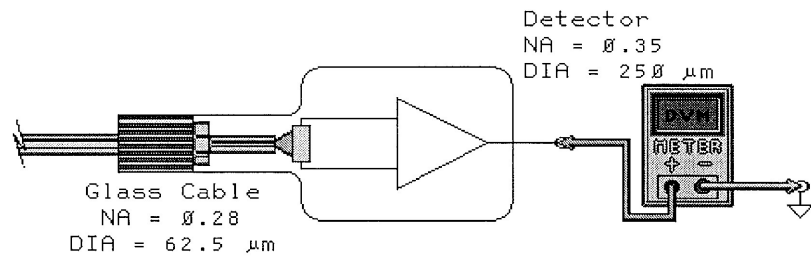
8. Calculate how much  $V_{FOR}$  changes (DV) when the light power ( $\phi_e$ ) changes from disconnected to connected.

$$DV = (V_{FOR} \text{ disconnected}) - (V_{FOR} \text{ connected})$$

DV = \_\_\_\_\_ mV



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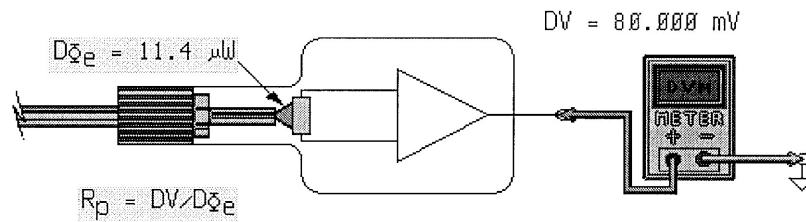


$$\text{LOSS}_{NA} = 20 \times \log(\text{NA}_1/\text{NA}_2)$$

$$\text{LOSS}_{UI} = 20 \times \log(\text{DIA}_1/\text{DIA}_2)$$

9. What are the NA and UI coupling losses at the fiber-to-detector connection?

- a. 14 dB    b. 12 dB    c. 0 dB    d. -14 dB



10. Assume that the actual FOT output power is near the typical value of 11.4 μW and calculate the receiver responsivity ( $R_p$ ).

$$R_p = \text{_____ mV}/\mu\text{W}$$

| Fiber-Optic Receiver Specifications |           |         |            |
|-------------------------------------|-----------|---------|------------|
| Specification                       | Min.      | Typ.    | Max.       |
| Responsivity ( $R_p$ )              | 5.1 mV/μW | 7 mV/μW | 10.9 mV/μW |
| Equivalent NA                       |           | 0.35    |            |
| Equivalent Diameter                 |           | 250 μm  |            |

$$R_p = DV/D0_e$$

The actual change in FOT output power  $D0_e$  could be anywhere between 5 and 20 μW.

11. Did you determine the actual FOR responsivity ( $R_p$ )?

- a. yes    b. no

# Light Detectors

| Fiber-Optic Receiver Specifications |                 |               |                  |
|-------------------------------------|-----------------|---------------|------------------|
| Specification                       | Min.            | Typ.          | Max.             |
| Responsivity ( $R_p$ )              | 5.1 mV/ $\mu$ W | 7 mV/ $\mu$ W | 10.9 mV/ $\mu$ W |
| Equivalent NA                       |                 | 0.35          |                  |
| Equivalent Diameter                 |                 | 250 $\mu$ m   |                  |

$$DV_{(min)} = D\Phi_e(min) \times R_{p(min)}$$

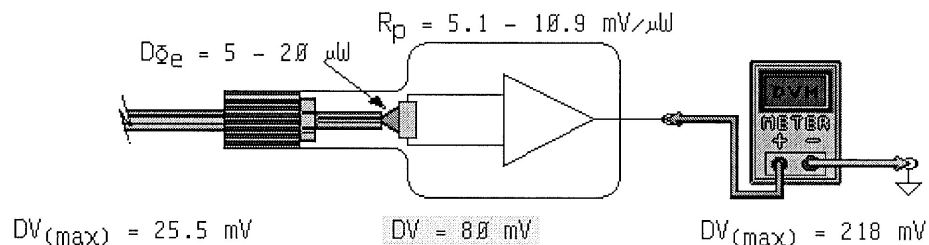
12. Assume the minimum change in FOT output power ( $D\Phi_e(min) = 5 \mu$ W) and calculate the smallest expected change in FOR output voltage.

$$DV_{(min)} = \text{_____ mVdc}$$

$$DV_{(max)} = D\Phi_e(max) \times R_{p(max)}$$

13. Assume the maximum change in FOT output power ( $D\Phi_e(max) = 20 \mu$ W) and calculate the largest expected change in FOR output voltage.

$$DV_{(max)} = \text{_____ mVdc}$$



14. Is the observed value of  $DV$  between  $DV_{(min)}$  and  $DV_{(max)}$ ?

- yes
- no

| Fiber-Optic Receiver Specifications |                 |               |                  |
|-------------------------------------|-----------------|---------------|------------------|
| Specification                       | Min.            | Typ.          | Max.             |
| Responsivity ( $R_p$ )              | 5.1 mV/ $\mu$ W | 7 mV/ $\mu$ W | 10.9 mV/ $\mu$ W |
| Equivalent NA                       |                 | 0.35          |                  |
| Equivalent Diameter                 |                 | 250 $\mu$ m   |                  |
| $V_{odc}$ ( $\Phi_e = 0 \mu$ W)     |                 | 0.7V          |                  |

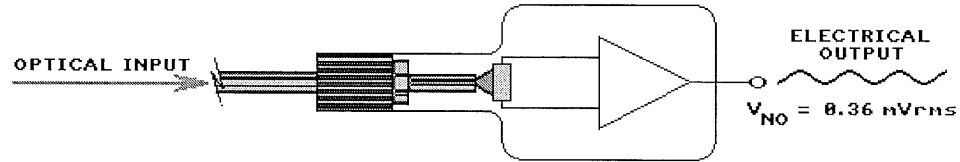
$V_{odc}$  is the dc voltage output from the FOT when no radiant power is supplied to the detector ( $\Phi_e = 0 \mu$ W).

You observed 730 mV at the FOR output with the light source disconnected.

15. Is your observed value of  $V_{odc}$  consistent with the fiber-optic receiver specifications?

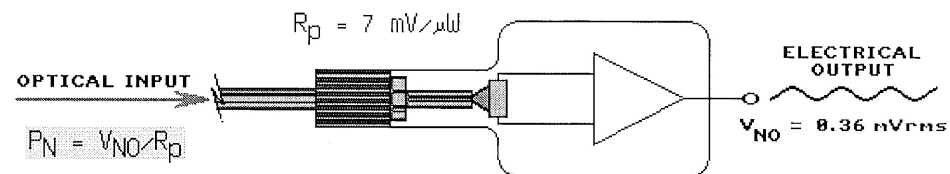
- yes
- no

# EXERCISE 4-1



The receiver generates both thermal and shot noise which appear as a random voltage on the FOT output.

The manufacturer specifies that the noise voltage ( $V_{NO}$ ) is a maximum of 0.36 mVrms with no optical input signal.



Receiver noise can also be specified as equivalent optical noise input power ( $P_N$ ) which is also called the **noise floor**.

$P_N$  is the radiant power ( $\phi_e$ ) which would produce  $V_{NO}$  if it were not generated by the receiver.

The noise floor ( $P_N$ ) is calculated by dividing  $V_{NO}$  by  $R_P$ .

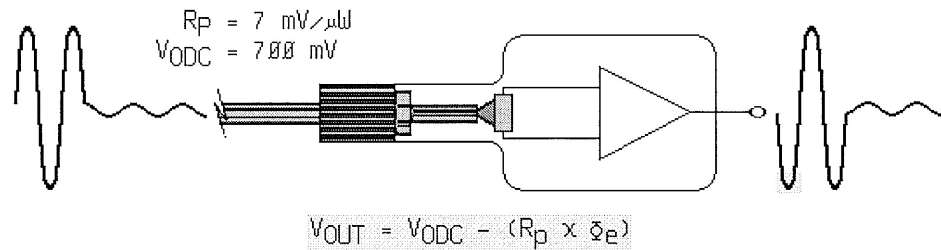
| Fiber-Optic Receiver Specifications  |                 |               |                  |
|--------------------------------------|-----------------|---------------|------------------|
| Specification                        | Min.            | Typ.          | Max.             |
| Responsivity ( $R_P$ )               | 5.1 mV/ $\mu$ W | 7 mV/ $\mu$ W | 10.9 mV/ $\mu$ W |
| Equivalent NA                        |                 | 0.35          |                  |
| Equivalent Diameter                  |                 | 250 $\mu$ m   |                  |
| DC output $V_{odc}$ ( $\phi_e = 0$ ) |                 | 0.7V          |                  |
| Noise $V_{NO}$ ( $\phi_e = 0$ )      |                 | 0.30 mVrms    | 0.36 mVrms       |

$$P_N = V_{NO}/R_P$$

16. Calculate the typical noise floor ( $P_N$ ) for this receiver.

$$P_N = \text{_____ } \mu\text{W}$$

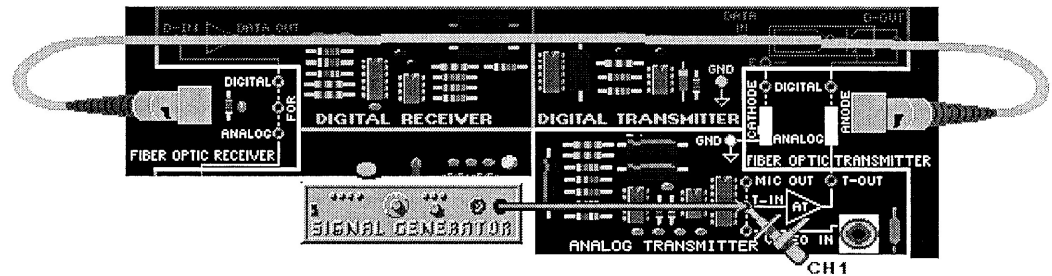
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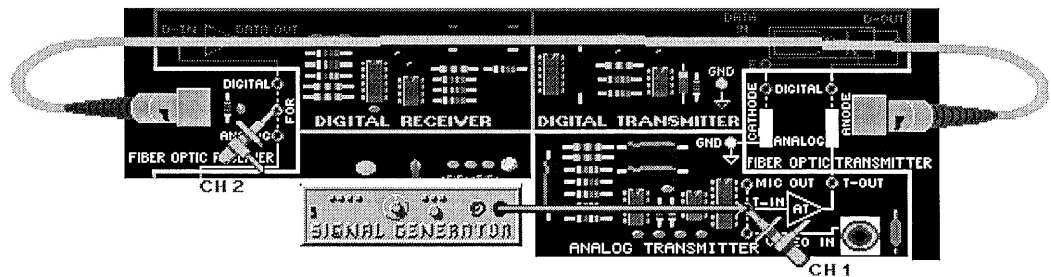
The receiver manufacturer specifies the maximum peak radiant input power ( $\phi_e$ ) at 55  $\mu\text{W}$  (-12.6 dBm).

17. Calculate the typical receiver output voltage ( $V_{OUT}$ ) when  $\phi_e$  is 55  $\mu\text{W}$ .

$V_{OUT} = \underline{\hspace{2cm}} \text{ mV}$

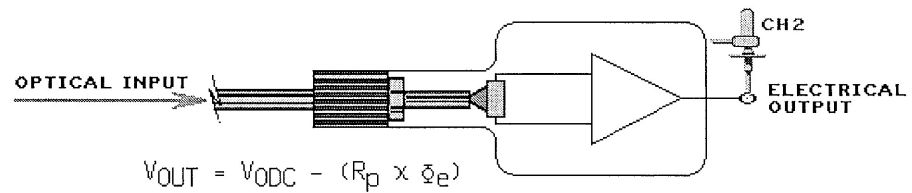


18. Connect the 1m glass cable between the FOT and FOR.
19. Connect an SIGNAL GENERATOR and oscilloscope CH 1 to T-IN.



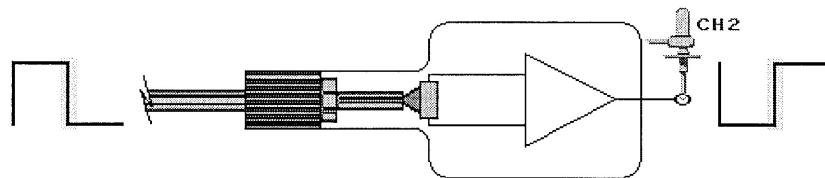
20. Adjust the generator for a 20 kHz 500 mVpk-pk sine wave at CH 1.
21. Connect CH 2 to FOR and adjust the scope to display several cycles of the input (CH 1) and output (CH 2) signals.

# EXERCISE 4-1



22. What is the phase relationship between the FOR optical input and the electrical output?

- a.  $0^\circ$
- b.  $45^\circ$
- c.  $90^\circ$
- d.  $180^\circ$



23. Adjust the generator to output a 20 kHz 500 mVpk-pk square wave (CH 1).

The ability of the FOR output to track changes in the optical input signal is determined by its bandwidth.

| Fiber-Optic Receiver Specifications    |                 |               |                  |
|----------------------------------------|-----------------|---------------|------------------|
| Specification                          | Min.            | Typ.          | Max.             |
| Responsivity ( $R_P$ )                 | 5.1 mV/ $\mu$ W | 7 mV/ $\mu$ W | 10.9 mV/ $\mu$ W |
| Equivalent NA                          |                 | 0.35          |                  |
| Equivalent Diameter                    |                 | 250 $\mu$ m   |                  |
| DC output $V_{ODC}$ ( $\Delta e = 0$ ) |                 | 0.7V          |                  |
| Noise $V_{NO}$ ( $\Delta e = 0$ )      |                 | 0.30 mVrms    | 0.36 mVrms       |
| Rise/Fall Time $t_r$ , $t_f$           |                 | 14 ns         | 19.5 ns          |
| BW- $t_r$ product ( $BW \times t_r$ )  |                 | 0.35          |                  |

Typically this receiver has a rise time of 14 ns and a 0.35 rise time bandwidth product ( $0.35 = BW \times t_r$ ).

24. Calculate the typical bandwidth for this receiver.

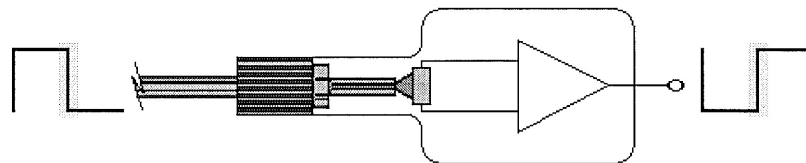
$BW = \underline{\hspace{2cm}}$  MHz

# Light Detectors

| Fiber-Optic Receiver Specifications   |                 |               |                  |
|---------------------------------------|-----------------|---------------|------------------|
| Specification                         | Min.            | Typ.          | Max.             |
| Responsivity ( $R_D$ )                | 5.1 mV/ $\mu$ W | 7 mV/ $\mu$ W | 10.9 mV/ $\mu$ W |
| Equivalent NA                         |                 | 0.35          |                  |
| Equivalent Diameter                   |                 | 250 $\mu$ m   |                  |
| DC output $V_{odc}$ ( $\phi_P = 0$ )  |                 | 0.7V          |                  |
| Noise $V_{NO}$ ( $\phi_P = 0$ )       |                 | 0.30 mVrms    | 0.36 mVrms       |
| Rise/Fall Time $t_r, t_f$             |                 | 14 ns         | 19.5 ns          |
| BW- $t_r$ product ( $BW \times t_r$ ) |                 | 0.35          |                  |
| Bandwidth BW                          |                 | 25 MHz        |                  |

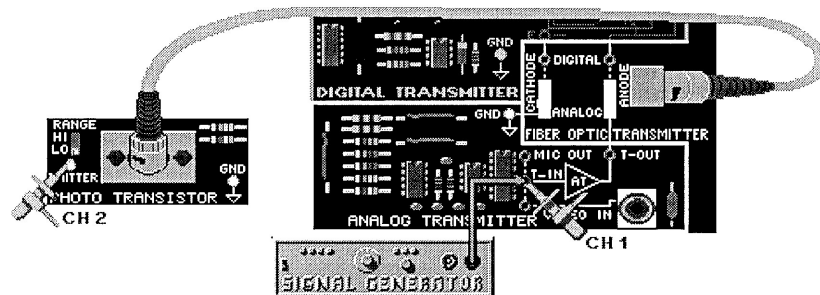
25. Calculate an estimate of the receiver's minimum bandwidth ( $BW = 0.35/t_r$ ).

BW = \_\_\_\_\_ MHz



26. Is the input signal fall time (CH 1) similar to the corresponding receiver output rise time (CH 2)?

- yes
- no

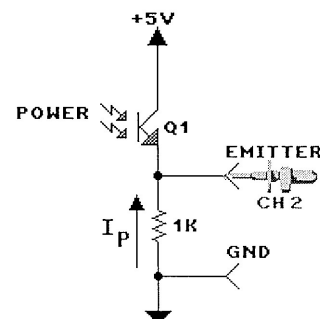


27. Connect the glass cable to the PHOTOTRANSISTOR, set the RANGE shunt to HI, and connect CH 2 to the PHOTOTRANSISTOR EMITTER.

Changes in the FOT output power are causing the phototransistor photocurrent to change.

The photocurrent is amplified by the forward current gain ( $\beta$ ) of the transistor, producing greater changes in  $I_P$ .

The 1 k $\Omega$  resistor converts  $I_P$  into the voltage displayed on CH 2.



# EXERCISE 4-1

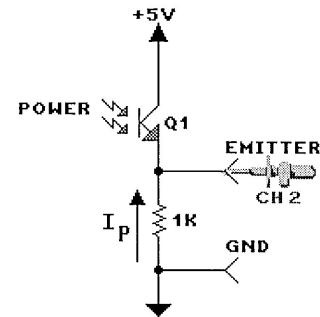
28. Carefully measure the rise time of the signal displayed on CH 2.

$t_r = \text{_____ ns}$

Capacitance limits the phototransistor bandwidth to approximately 438 kHz.

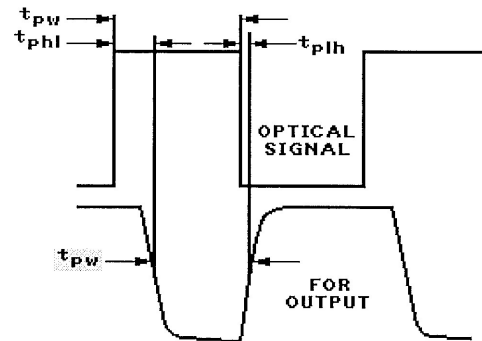
Reducing the light detector bandwidth from 25 MHz to 438 kHz increased the rise time from 14 ns to 800 ns.

Negative feedback can be used to reduce the phototransistor gain, increase circuit bandwidth, and reduce rise time.



The time required for the FOR to propagate a high ( $t_{p1h}$ ) level is not always equal to the low level propagation time ( $t_{p1l}$ ).

The difference between the propagation times ( $t_{p1l} - t_{p1h}$ ) distorts the output pulse width ( $t_{pw}$ ).



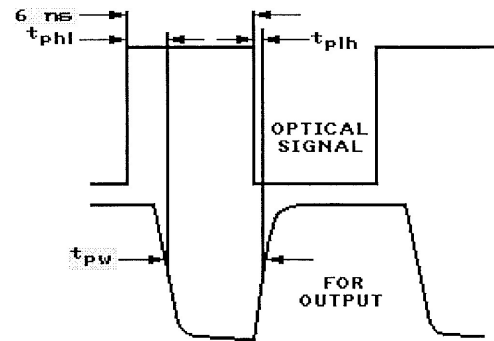
| Fiber-Optic Receiver Specifications     |                 |               |                   |
|-----------------------------------------|-----------------|---------------|-------------------|
| Specification                           | Min.            | Typ.          | Max.              |
| Responsivity ( $R_p$ )                  | 5.1 mV/ $\mu$ W | 7 mV/ $\mu$ W | 10.9 mV/ $\mu$ W  |
| Equivalent NA                           |                 | 0.35          |                   |
| Equivalent Diameter                     |                 | 250 $\mu$ m   |                   |
| DC output $V_{odc}$ ( $\phi_e = 0$ )    |                 | 0.7V          |                   |
| Noise $V_{NO}$ ( $\phi_e = 0$ )         |                 | 0.30 mVrms    | 0.36 mVrms        |
| Rise/Fall Time $t_r, t_f$               |                 | 14 ns         | 19.5 ns           |
| BLW- $t_r$ product ( $BLW \times t_r$ ) |                 | 0.35          |                   |
| Bandwidth BLW                           |                 | 25 MHz        |                   |
| PW Dist. ( $t_{p1l} - t_{p1h}$ )        |                 |               | 2 ns (40 $\mu$ W) |

The manufacturer specifies that the FOR pulse width distortion ( $t_{p1l} - t_{p1h}$ ) is not more than 2 ns when a 40  $\mu$ W input signal is used.

# Light Detectors

The optical signal has a 6 ns pulse width and the FOR  $t_{phl}-t_{plh}$  is 2 ns.

29. Calculate the pulse width at the FOR output?
- 8 ns
  - 6 ns
  - 4 ns
  - 2 ns



## CONCLUSIONS

- Light detectors are subject to coupling losses between the optical fiber and light transducer.
- Responsivity is a measure of the light detector's response to light power.
- The difference between rise and fall propagation times produces pulse-width distortion at the detector output.

## REVIEW QUESTIONS

1. Using a light detector with an increased bandwidth
  - a. decreases pulse width.
  - b. increases fall time.
  - c. decreases rise time.
  - d. increases coupling loss.
2. The fiber optic receiver (FOR) on the FIBER OPTIC COMMUNICATIONS circuit board
  - a. uses a photodiode.
  - b. converts photocurrent to voltage.
  - c. has an inverting output.
  - d. All of the above.
3. Which is a measure of detector response to optical power?
  - a. responsivity
  - b. bandwidth
  - c. equivalent optical noise input power
  - d. equivalent diameter



# EXERCISE 4-1

4. A phototransistor has an input power of  $2\text{ }\mu\text{W}$  and a photocurrent of  $20\text{ mA}$ . What is the transistor's responsivity?
- a.  $10\text{ mV}/\mu\text{W}$
  - b.  $10\text{ mA}/\mu\text{W}$
  - c.  $0.1\text{ mV}/\mu\text{W}$
  - d.  $0.1\text{ mA}/\mu\text{W}$

$$\text{LOSS}_{\text{UI}} = 20 \times \log(\text{DIA}_1/\text{DIA}_2)$$

5. What is the attenuation due to UI when a  $100/140\text{ }\mu\text{m}$  glass fiber is coupled to an FOR with a  $110\text{ }\mu\text{m}$  effective diameter?
- a.  $-2.1\text{ dB}$
  - b.  $0\text{ dB}$
  - c.  $0.83\text{ dB}$
  - d.  $2.1\text{ dB}$